LPT-ORSAY-12-112

Effect of Anomalous Couplings on the Associated Production of a Single Top Quark and a Higgs Boson at the LHC

Pankaj Agrawal [a*], Subhadip Mitra [b†] and Ambresh Shivaji [a‡]

a) Institute of Physics, Saink School Post, Bhubaneswar 751 005, India
b) Laboratoire de Physique Théorique, CNRS - UMR 8627,
Bâtiment 210, Univ. Paris-Sud 11, F-91405 Orsay Cedex, France

November 18, 2012

Abstract: We consider the production of a single top quark in association with a Higgs boson at the LHC. In particular, we compute the cross sections for the processes $pp \to thj$, thb, thW, $thjj$, $thjb$, $thWj$, $thWb$ in presence of the anomalous Wtb, WWh and tth couplings. We find that the anomalous Wtb and tth couplings can enhance the cross sections significantly. If these couplings are indeed anomalous, then with enough data, one should be able to observe the production of the Higgs boson in association with a single top quark.

Keywords: Single top, Higgs boson, LHC, Anomalous couplings

1 Introduction

So far the Standard Model (SM) has been remarkably successful in explaining the data from the modern hadron colliders like the Tevatron at Fermilab or the Large Hadron Collider (LHC) at CERN. We have now very strong indications that the only missing piece of the SM, the Higgs boson has been discovered [1, 2]. On the other hand, there does not seem to be any stand-out signal of any of the beyond the Standard Model (BSM) scenarios. There exist wide variety of scenarios with specific signatures to validate them. Some of these scenarios have overlapping signatures. Therefore, even if one finds a new signal, it may require a lot of work to ensure the connection of the signal with a specific model. Hence, apart from model-specific analysis of the data, it will also be useful to look for BSM scenarios in model independent ways. One can do so by constructing suitable effective Lagrangians. These effective Lagrangians have terms that are consistent with some of the aspects of the SM, in

*email: agrawal@iopb.res.in
†email: subhadip.mitra@th.u-psud.fr
‡email: ambresh@iopb.res.in

particular symmetries, but contain higher dimensional (non-renormalizable) operators. Because of the non-renormalizable nature of the extra terms, these effective Lagrangians can only be used in a restricted domain of the energy scales. The particle content of these effective Lagrangian models is same as that of the SM. The extra terms in the Lagrangian can introduce new interactions, or they can modify the existing interactions of some of the particles. In particular, we note that, we can have modifications of the Wtb, tth and WWh vertices that can be parametrized as anomalous couplings.

After the discovery of the Higgs boson at the LHC, it would be important to study various properties of it. In particular, one would like to study the production of the Higgs boson via all possible channels. One such category of channels is the production of the Higgs boson in association with a single top quark. In these processes, there can be additional particles, apart from the top quark and the Higgs boson. Some of these processes have been studied within the context of the SM [3]. These processes are similar to the single top quark production processes. In this case, a Higgs boson is emitted either from the top quark or the W boson. Due to the similarity with the single top quark production processes, one would expect these processes to contribute significantly to the Higgs boson production at the LHC. However, as pointed out in Ref. [3], for the Higgs boson mass, $m_h < 200$ GeV, the cross sections of such processes turn out to be rather small compared to what is expected from the single top quark production at the LHC. At the LHC, for $m_h \sim 100 - 150$ GeV, the dominant contributions come from the t-channel W exchange process, $pp \to thj$ and associated production with a W-boson, $pp \to tWh$. The authors of Ref. [3] demonstrated that for both of these channels, there is a destructive interference between the diagrams where the Higgs boson is emitted from the top quark and ones with the Higgs boson emitted from the W boson. Because of the small cross sections, these channels are generally not considered as significant to measure the properties of the Higgs boson. However, inclusion of anomalous couplings changes the picture. The cross sections can be significantly enhanced to make these processes phenomenologically useful. In this paper, we study the effect of anomalous Wtb, tth and WWh vertices on the cross section and distributions of the single top quark production in association with a Higgs boson at a hadronic collider. We find that with the currently allowed ranges of the anomalous couplings, the enhancement can be more than a factor of ten for some values of the Wtb and tth anomalous couplings and as a result the associated production of a single top quark with the Higgs boson can become significant at the LHC. Moreover, once observed, these channels can give us useful information about some of the anomalous couplings.

The organization of the paper is as follows. In section 2, we describe the processes under consideration. In section 3, we discuss the anomalous Wtb, tth and WWh couplings. In section 4, we present the numerical results. In section 5, we discuss the possibility of observing these processes at the LHC. In the last section, we present our conclusions.

2 Processes

In this section we describe those processes for the production of a Higgs boson where it is produced in association with a single top quark. In our analysis we include the tree-level leading order and the sub-leading order processes (*i.e.,* processes with an extra jet) that have significant cross sections. The

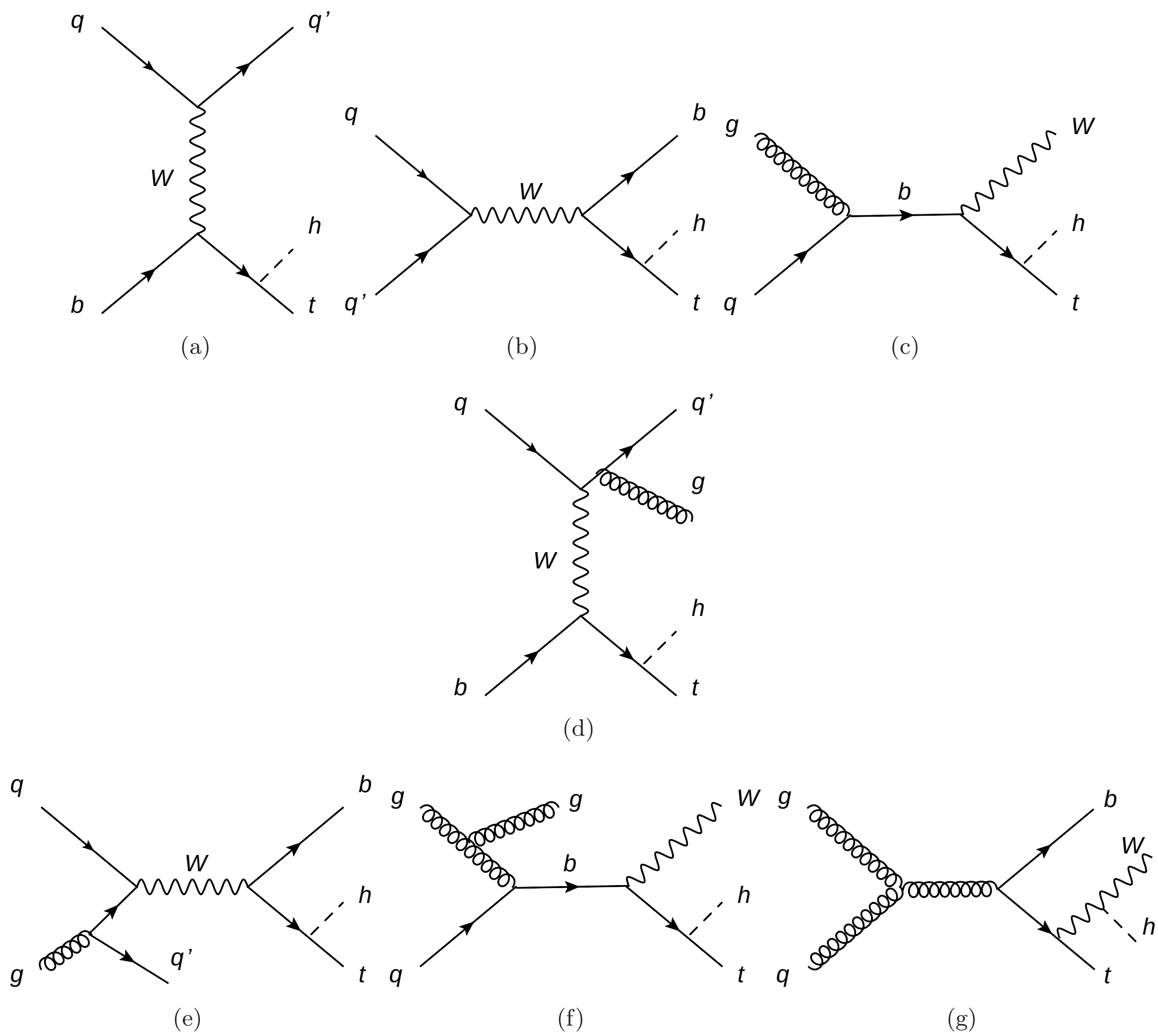

Figure 1: Representative Feynman diagrams for the processes listed in Eqs. 1 - 7.

leading order processes are following

$$p\,p \;\rightarrow\; t\,h\,j\,X, \tag{1}$$

$$p\,p \;\rightarrow\; t\,h\,b\,X, \tag{2}$$

$$p\,p \;\rightarrow\; t\,h\,W\;X \tag{3}$$

and the processes with an extra jet are,

$$p\,p \;\rightarrow\; t\,h\,j\,j\,X, \tag{4}$$

$$p\,p \;\rightarrow\; t\,h\,j\,b\,X, \tag{5}$$

$$p\,p \;\rightarrow\; t\,h\,W\,j\,X, \tag{6}$$

$$p\,p \;\rightarrow\; t\,h\,W\,b\,X. \tag{7}$$

Here 'j' represents a jet from a light quark (excluding bottom quark) or a gluon. Representative parton level diagrams are displayed in Fig. 1. The leading order processes can be classified into three categories:

1. process with W boson in t-channel, $pp \to thj$,

2. process with W boson in s-channel, $pp \to thb$ and

3. process with W boson in the final state, $pp \to thW$.

As we shall see, the t channel process has the largest cross section, while the s channel process has the smallest cross section. The subleading diagrams can be obtained by adding an extra jet (either light or b-jet) to these three processes. All the processes contain one tbW vertex and one tth or WWh vertex. That is why we study the effect of anomalous couplings in these vertices on the cross sections.

The subleading processes can also have relatively significant cross sections. However, one has to be careful while computing their contribution at the matrix element level. These extra jets can be soft and thus lead to infrared divergences. To avoid the soft jet contribution one has to set a reasonably large p_T cut for them. Apart from this, these is also the possibility of over counting. Like, *e.g.*, in the case of the process $pp \to thjj$, the jet pair can come from an on-shell W decay making it a $pp \to thW$ process. Hence to estimate the cross section of this process we don't allow any on-shell W. Similarly, for the process $pp \to thWb$, the bW pair can come from the decay of an on-shell top quark. However, in that case the actual process will be $pp \to tth$, which has a much larger cross section than the th production. To avoid such a situation, in our calculation, we allow only one of the top quark to go on-shell.

3 Anomalous Interactions

As we discussed above, the processes under considerations have three electroweak vertices - tbW, tth, and WWh. (Since Wqq' vertex with q and q' being the light quarks is seriously constrained, we don't include the possibility of this vertex being anomalous.) We consider the general possible modification of these vertices due to BSM interactions. The possible general structure of these vertices have been extensively discussed in the literature [4–8]. One parametrizes the effect of heavy BSM physics by introducing the most general independent set of higher dimensional operators that satisfies the gauge symmetries of the SM. However these terms generally reduce to simpler and more familiar forms when relations such as the equations of motion of the fields are used. We will use these simpler forms for our calculations.

Anomalous Couplings in the tbW Vertex

In the SM, the tbW coupling is V-A type. Therefore, only the left-handed fermion fields couple to the W boson. So, it allows only a left-handed top quark to decay into a bottom quark and a W boson. However, the BSM physics can generate several other possible tbW couplings. One can write down the

most general tbW interaction that includes corrections from dimension-six operators [4],

$$\mathcal{L}_{tbW} = \frac{g}{\sqrt{2}}\bar{b}\left[\gamma^{\mu}\left(f_{1L}P_L + f_{1R}P_R\right)W^{-}_{\mu} + \frac{\sigma^{\mu\nu}}{m_W}(f_{2L}P_L + f_{2R}P_R)\left(\partial_{\nu}W^{-}_{\mu}\right)\right]t + H.c., \tag{8}$$

where, in general, $f_{iL/R}$'s are complex dimensionless parameters. Also $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$. In the SM, $f_{1L} = V_{tb} \approx 1$ while $f_{1R} = f_{2L} = f_{2R} = 0$. In our analysis, we assume the $f_{iL/R}$'s to be real for simplicity.

Both recent LHC data and Tevatron data put bound on these parameters. Till now Tevatron puts more stringent bound on these as compared to the LHC [9]. The Tevatron bounds are roughly

$$\begin{aligned} 0.8 \lesssim &\quad f_{1L} &\lesssim 1.2\,, \\ -0.5 \lesssim &\quad f_{1R} &\lesssim 0.5\,, \\ -0.2 \lesssim &\quad f_{2L/R} &\lesssim 0.2\,. \end{aligned} \tag{9}$$

Notice that these bounds are quite loose. Therefore, the SM results can have significant corrections.

Anomalous Couplings in the tth Vertex

In the SM, the top quark couples with the Higgs boson via the Yukawa coupling. In the effective theory, the most general vertex for tth interaction can be parametrized as [5],

$$\mathcal{L}_{\bar{t}th} = -\frac{m_t}{v}\bar{t}\left[\left(1 + y_t^V\right) + i y_t^A \gamma_5\right] th. \tag{10}$$

In the SM, $y_t^V = y_t^A = 0$ and the first non-zero contributions to y_t^V and y_t^A come from dimension six operators.

There is no significant experimental bound on the anomalous tth couplings and unitarity constrains allow order one values for y_t^V and y_t^A [6].

Anomalous Couplings in the WWh Vertex

The new higher dimensional operators that can contribute to WWh Vertex can be written as [7, 8]

$$\begin{aligned} \mathcal{L}_{WWh} \;=\;& g^1_{WWh}\left(W^{+}_{\mu\nu}W^{-\mu} + W^{-}_{\mu\nu}W^{+\mu}\right)\partial^{\nu}h + g^2_{WWh}\left(W^{-}_{\mu\nu}W^{+\mu\nu}\right)h \\ & - g^3_{WWh}\frac{m_W^2}{v}\left(W^{+}_{\mu}W^{-\mu}\right)h, \end{aligned} \tag{11}$$

where

$$W^{\pm}_{\mu\nu} = \partial_{\mu}W^{\pm}_{\nu} - \partial_{\nu}W^{\pm}_{\mu} \pm ig\left(W^3_{\mu}W^{\pm}_{\nu} - W^3_{\nu}W^{\pm}_{\mu}\right). \tag{12}$$

The third term in Eq. 11 comes form the normalization of the Higgs boson kinetic term which gets modified due to higher dimensional operators. The constraints coming from the electroweak precision

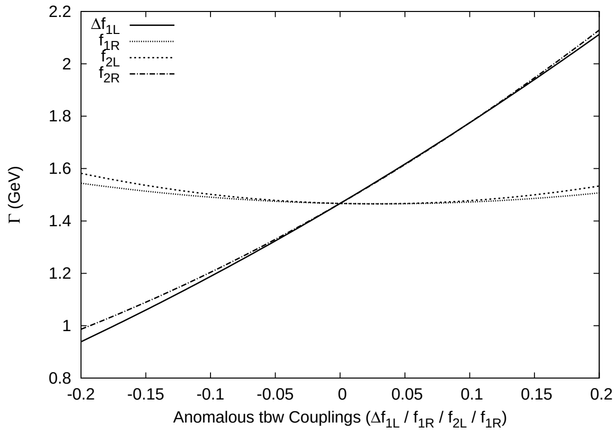

Figure 2: Dependence of top quark width on the anomalous couplings present in the tbW vertex (defined in Eq. 8) – $\Delta f_{1L} = f_{1L} - 1$, f_{1R}, f_{2L} and f_{2R}.

data are [10],

$$-0.16\ \mathrm{TeV}^{-1} \lesssim \quad g^1_{WWh} \quad \lesssim 0.13\ \mathrm{TeV}^{-1}\,, \tag{13}$$

$$-0.26\ \mathrm{TeV}^{-1} \lesssim \quad g^2_{WWh} \quad \lesssim 0.29\ \mathrm{TeV}^{-1}\,. \tag{14}$$

There is no significant bound on the coupling g^3_{WWh}.

4 Results

The main decay mode of the top quark is $t \to bW$ with a branching ratio of almost 99%. Therefore, the presence of anomalous couplings in the tbW vertex can modify the top quark width significantly. With anomalous couplings, the top quark width is

$$\begin{aligned}\Gamma(t \to b\,W) = \frac{G_F}{8\pi\sqrt{2}}\, m_t^3\,(1-x^2)\Big[(1+x^2-2x^4)(f_{1L}^2+f_{1R}^2) \\ +(2-x^2-x^4)(f_{2L}^2+f_{2R}^2)+6x(1-x^2)(f_{1L}f_{2R}+f_{2L}f_{1R})\Big],\end{aligned} \tag{15}$$

where $x = M_W/m_t$.

In Fig. 2, we show the dependence of the decay width of the top quark on $\Delta f_{1L} = f_{1L} - 1$, f_{1R}, f_{2L} and f_{2R}. We see that the top quark width can change by about $\pm 50\%$ on varying the values of f_{1L} or f_{2R}. However, the width is relatively immune to the change in the values of f_{2L} or f_{1R}. We can understand this as follows. Since, $f_{1L} = 1 + \Delta$ and other couplings are $\sim \Delta$, this implies

$$f_{1L}^2 \simeq 1 + 2\Delta;\; f_{1R}^2 = f_{2L}^2 = f_{2R}^2 = f_{2L}f_{1R} \simeq \Delta^2;\ \text{and}\ f_{1L}f_{2R} \simeq \Delta. \tag{16}$$

This explains the strong dependence of the decay width on f_{1L} and f_{2R}. The weak dependence of the

width on the couplings f_{2L} and f_{1R} is essentially due to the absence of the terms proportional to $f_{1L}f_{1R}$ and $f_{1L}f_{2L}$. One needs to include the modified widths when considering the decays of the top quark.

To compute the cross sections for the processes involved we use Madgraph5 [11] with LO CTEQ6L1 parton distribution functions [12]. We have used the following kinematic cuts on the final state partons,

$$P_T^J > 30 \text{ GeV}, \ |\eta_{\rm J}| < 5.0, \ \Delta{\rm R(J,j)} = \sqrt{\Delta\left(\eta_{\rm J,j}\right)^2 + \left(\Delta\phi_{\rm J,j}\right)^2} > 0.4 \tag{17}$$

where J denotes either a light jet or a b-jet. Unlike the tbW and tth anomalous couplings, we find that the associated production of a single top quark with a Higgs boson is not very sensitive to any variation of WWh anomalous couplings. If one varies $g^i_{WWh}(i = 1, 2)$ within the allowed ranges (given above) the cross sections for the different processes vary marginally (about a few percent). The same is true for an $\mathcal{O}(1)$ variation of g^3_{WWh}. So for all results in this section, we have set anomalous WWh couplings to their SM values (*i.e.*, $g^i_{WWh} = 0$).

In Fig. 3, we show the dependence of the cross sections of the processes thj, thb and thW on f_{1L}, f_{1R}, f_{2L}, f_{2R}, y_t^V, and y_t^A. The SM value of the cross section for the thj process is about 60 fb. The variation in f_{1L} and f_{2L} does not increase the cross section much. However, at the edge of allowed values of f_{2R} cross section can double. There is almost no change in the cross section on varying f_{1R}. This overall behavior is almost like that of the top quark width. So, it can be understood similarly. However, there is a strong dependence on the Yukawa couplings. As we shall see below, there exist allowed regions in the phase space where cross section can increase more than 10 times and approaches 600-800 fb. The cross sections of the other two processes thb and thW do not depend significantly on the anomalous tbW coupling. However, the cross section of the thb can almost double with the allowed range of the Yukawa couplings.

In Fig. 4, we show the dependence of the cross sections of the processes $thjj, thbj, thWb$ and $thWj$ on f_{1L}, f_{1R}, f_{2L}, f_{2R}, y_t^V, and y_t^A. The behavior of the $thjj$ and $thbj$ processes is similar to what we find above. The variation in f_{1L} and f_{2L} changes cross sections marginally; the variation in f_{1R} has almost no impact on the cross sections. However, at the edge of the allowed parameter values of f_{2R}, the cross sections can double. The cross sections of the processes $thWb$ and $thWj$ have very weak dependence on the anomalous tbW coupling parameters. However, as earlier, the cross sections have strong dependence on the Yukawa couplings.

The plots in Fig. 3 and Fig. 4 show variation with respect to change in one parameter, while the other parameters are kept at the SM value. Of course, we can choose values of all parameters away from the SM values which will give larger cross sections. We have chosen a set of values which may favor the larger cross sections. This set of values and the cross sections for those values are given in Table 1. The set of parameters $\mathcal{P}_0$ corresponds to the SM values. The cross sections of the processes are adding up to about 150 fb. However, there exist parameter sets where the cross sections can add up to more than 1 pb. For most of the listed processes, the cross sections can increase as much as fifteen times or more. With these values of the cross sections, it may be possible to isolate the production of the Higgs boson in association with a top quark from the background and observe it at the LHC.

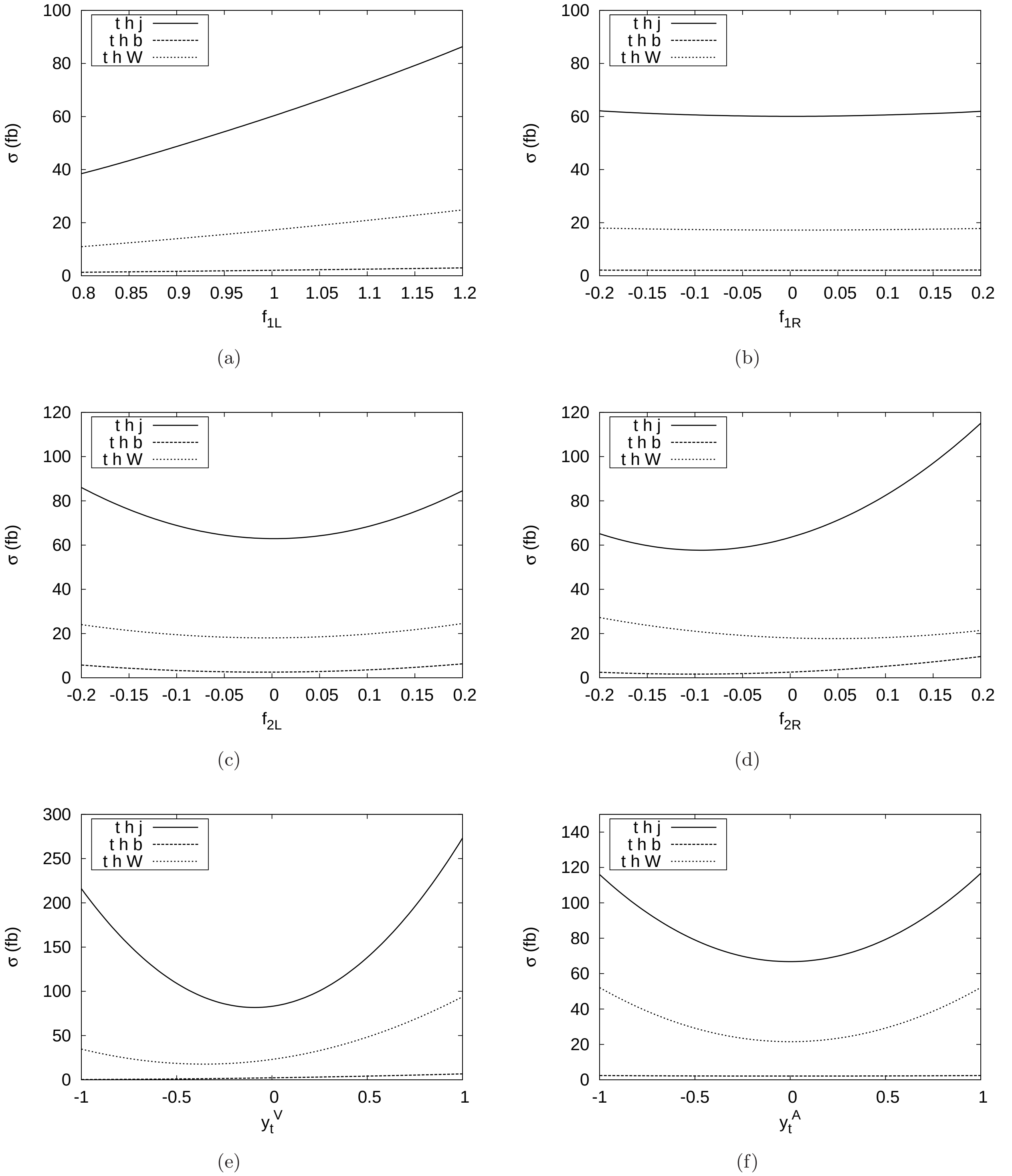

Figure 3: Dependence of the leading order partonic cross section on f_{1L}, f_{1R},f_{2L}, f_{2R}, y_t^V, y_t^A. Here the individual contribution of the three separate subprocesses are marked by the final state particles. Eq. 17 shows the cuts used on the final state partons.

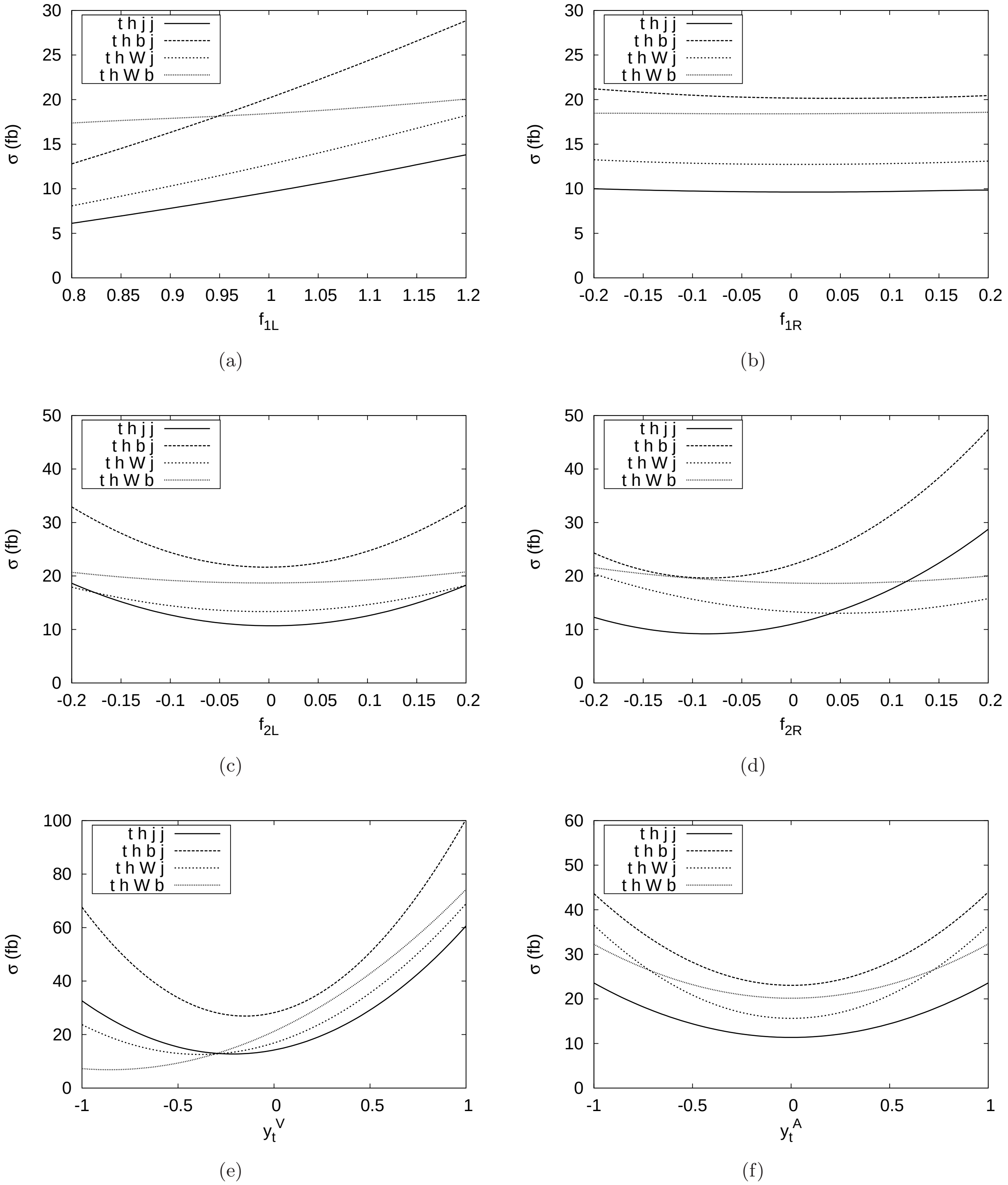

Figure 4: Dependence of the partonic cross section for processes with 4 particles in the final states on f_{1L}, f_{1R},f_{2L}, f_{2R}, y_t^V, y_t^A. The individual contribution of the separate subprocesses are marked by the final state particles. Here j stands for a light jet. Eq. 17 shows the cuts used on the final state partons.

Parameter Set	$\sigma_{pp\to thj}$ (fb)	$\sigma_{pp\to thb}$ (fb)	$\sigma_{pp\to thW}$ (fb)	$\sigma_{pp\to thjj}$ (fb)	$\sigma_{pp\to thbj}$ (fb)	$\sigma_{pp\to thWj}$ (fb)	$\sigma_{pp\to thWb}$ (fb)
$\mathcal{P}_0$	59.6	2.1	17.1	9.6	20.1	12.7	18.4
$\mathcal{P}_1$	180.1	2.7	51.6	35.1	72.4	35.8	18.3
$\mathcal{P}_2$	382.9	3.2	105.4	69.6	144.3	73.0	30.3
$\mathcal{P}_3$	472.0	3.4	116.7	86.7	153.3	79.9	32.9
$\mathcal{P}_4$	567.0	53.0	129.9	169.0	246.1	95.3	93.5
$\mathcal{P}_5$	602.3	29.4	250.7	163.8	263.3	184.2	117.1
$\mathcal{P}_6$	875.2	64.4	229.8	241.5	363.5	167.0	107.4

Parameter Set	f_{1L}	f_{1R}	f_{2L}	f_{2R}	y_t^V	y_t^A
$\mathcal{P}_0$	1.0	0.0	0.0	0.0	0.0	0.0
$\mathcal{P}_1$	0.8	0.2	0.2	0.2	-1.0	-1.0
$\mathcal{P}_2$	1.2	0.2	0.2	0.2	-1.0	-1.0
$\mathcal{P}_3$	1.2	0.2	0.2	-0.2	-1.0	-1.0
$\mathcal{P}_4$	0.8	0.2	0.2	0.2	1.0	1.0
$\mathcal{P}_5$	1.2	0.2	0.2	-0.2	1.0	1.0
$\mathcal{P}_6$	1.2	0.2	0.2	0.2	1.0	1.0

Table 1: Cross-sections for different single top quark and Higgs boson associated production processes for six different extremal choices of anomalous coupling parameters denoted by $\mathcal{P}_{i=1,\ldots,6}$ (explained in the lower table). The set $\mathcal{P}_0$ corresponds to the SM couplings.

5 Observability

We now consider the possible signatures of these processes and the backgrounds. We just wish to argue that background to some of the processes can be manageable. The results of a detailed signal and background studies would be reported elsewhere.

For $m_h \approx 125$ GeV, the primary decay mode of the Higgs boson would be $h \to b\bar{b}$. For the signature to be viable, the accompanying top quark would need to decay semileptonically. If the top quark decays into jets only, then the QCD backgrounds due to the production of the multijet events would overwhelm the signal. Therefore, the main signatures of the Higgs boson produced through these channels would be 'isolated leptons + 3/4 bottom jets + jets'. For these signatures, there will be two classes of backgrounds: 1) direct backgrounds and 2) mimic backgrounds. The direct backgrounds will have at least the particles of the signature; there can be extra particles. The mimic background will have jets which can mimic bottom jets. The example of processes that can give rise to 'isolated leptons + 3/4 bottom jets' directly are are $pp \to t\bar{t}b/\bar{b}X, ttbX, WbbbbX, ttZX, WZZX$. The example of the mimic backgrounds, where at least one of the light parton/gluon jet has to fake a bottom jet, are $pp \to ttjX, ttjjX, ttWjX, ttZjX, WbbjX, WbbjjX$.

Largest background will come from the direct and mimic backgrounds where the top quark has been produced through the strong interaction. The direct backgrounds from $pp \to ttbX, ttbbX, ttZX$ have cross sections of the order of 3.5, 1.5 and 0.5 pb respectively. The processes $pp \to WZZX, WbbbbX$ have much smaller cross sections of 0.01 and 0.03 pb respectively. The mimic backgrounds will not be

larger than these backgrounds when we include the mimic probability of the order of 1%. If we look at the signal cross sections including anomalous couplings, then they can be of the order of 500 fb. In such a case, we can have significance of more than 5 with even about 10 fb^{-1} of integrated luminosity. For a smaller signal cross section, i.e., of the order of 50 fb, one may need to look at the exclusive signature. This is because the background usually has more than one top quark, so have more particles in the final state than the signal events. Such strategies have been employed earlier.

Other two important decay modes of the Higgs boson for the Higgs boson of the mass around 125 GeV are $h \to \tau\tau, WW^*$. Both have branching ratios of few percents. Here the decay mode $h \to \tau\tau$ can be useful with the detection of tau-jets. Then a signature of the type "isolated lepton + 2 tau-jets + 1/2 bottom jets" can be useful. At a longer time scale even $h \to WW^*$ can also be useful if one looks at "one/two isolated leptons + two-tau jets + 1/2 bottom jet". All these signatures require detailed study using event generators such as PYTHIA.

6 Conclusions

In this paper, we have investigated the effect of anomalous couplings in the tbW, tth and WWh vertices on the associated production of a single top quark with the Higgs boson. Within the SM, these processes have small cross sections. However, we find that anomalous Wtb and tth couplings can enhance the cross sections of the processes significantly. In particular, the cross sections of the different processes involved are not only sensitive to the Yukawa couplings, but also to f_{1L}, f_{2R}. For some combinations of these couplings, the enhancement can be more than a factor of 10. The combined cross section of the processes under consideration can be more than 1 pb. Anomalous WWh coupling plays an innocuous role. Although we refrain from rigorous background analysis in this paper, we argue that it may be possible to observe the Higgs boson through these processes if look at the signatures "exclusive isolated lepton + 3/4 bottom jets". Given the strong experimental evidence for the Higgs boson, these processes will be observed at some point in the future.

Note Added

When we were writing this paper at the final stage of the project, two different papers appeared [13,14] that discuss th production. The first one considers $pp \to tjh$ with $h \to \gamma\gamma$ while the second one discusses $pp \to thj$ and $pp \to thjb$ processes.

References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].

[3] F. Maltoni, K. Paul, T. Stelzer and S. Willenbrock, Phys. Rev. D **64**, 094023 (2001) [hep-ph/0106293].

[4] J. A. Aguilar-Saavedra, Nucl. Phys. B **812**, 181 (2009) [arXiv:0811.3842 [hep-ph]].

[5] J. A. Aguilar-Saavedra, Nucl. Phys. B **821**, 215 (2009) [arXiv:0904.2387 [hep-ph]].

[6] K. Whisnant, B. -L. Young and X. Zhang, Phys. Rev. D **52**, 3115 (1995) [hep-ph/9410369].

[7] K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, Phys. Rev. D **48**, 2182 (1993).

[8] V. Barger, T. Han, P. Langacker, B. McElrath and P. Zerwas, Phys. Rev. D **67**, 115001 (2003) [hep-ph/0301097].

[9] J. A. Aguilar-Saavedra, N. F. Castro and A. Onofre, Phys. Rev. D **83**, 117301 (2011) [arXiv:1105.0117 [hep-ph]].

[10] B. Zhang, Y. -P. Kuang, H. -J. He and C. P. Yuan, Phys. Rev. D **67**, 114024 (2003) [hep-ph/0303048].

[11] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, JHEP **1106**, 128 (2011) [arXiv:1106.0522 [hep-ph]].

[12] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, JHEP **0207**, 012 (2002) [hep-ph/0201195].

[13] S. Biswas, E. Gabrielli and B. Mele, arXiv:1211.0499 [hep-ph].

[14] M. Farina, C. Grojean, F. Maltoni, E. Salvioni and A. Thamm, arXiv:1211.3736 [hep-ph].